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Co-combustion of coal with printing and dyeing sludge: Numerical simulation of the process and related NO_X emissions

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HIGHLIGHTS

- PDS content, moisture content and SA distribution greatly affect the co-combustion.
- The more the PDS content is, the higher the NO_X concentration in global emissions is.
- There are higher NO_X emission and lower temperature under higher moisture content.
- Blending with 10% PDS of 40% moisture content is feasible and reasonable.
- The best SA distribution is the ratio (from upper to bottom) of 3:1:2:4.

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ABSTRACT

The co-combustion of coal with printing and dyeing sludge (PDS) in a pulverized coal power plant was simulated based on the computational fluid dynamics method. The co-combustion characteristics and NO_X emissions were analyzed to determine the optimal PDS content, moisture content, and secondary air (SA) distribution scheme. This study comprised three main parts. The first part was a comparative analysis of blending coal with different amounts of PDS, which indicated that the overall temperature level of the furnace decreased slightly and the NO_X emissions increased gradually as the PDS content increased. The second part was a comparative analysis of blending coal with PDS at different moisture contents, which indicated that the furnace temperature was lower and the NO_X emissions were higher with as the moisture content increased. Furthermore, after analyzing the combustion characteristics and NO_X emissions, we found that blending with 10% PDS at a moisture content of 40% was the most reasonable strategy based on a constant total lower calorific value. In the third part, SA optimization analysis indicated that the SA distribution clearly affected the combustion characteristics and pollutant emission, where an SA ratio from top to bottom of 3:1:2:4 was the best SA distribution scheme.

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1. Introduction

Traditionally, the printing and dyeing sludge (PDS) generated during the treatment of wastewater in the printing and dyeing industry has been regarded as a troublesome and unavoidable by-product [1]. Moreover, PDS is a complex waste that contains organic and inorganic substances, with a high percentage of water [2]. However, more stringent environmental protection policies and higher controls regarding the environment have led to greater limitations on the reuse of sludge. In addition, PDS emissions are increasing rapidly with the development of the printing and dyeing industry in China. In particular, the amount of wastewater produced from the printing and dyeing industry exceeds 300 million tons each year in Guangdong province alone in China. Therefore, it is necessary to develop a suitable technique to dispose of PDS effectively, economically, and securely.

Due to the inadequacy of landfill disposal, high costs, and environmental protection policies, the common disposal technologies such as landfill, fertilizers on agricultural land, and dumping into the sea have been restrained in many application areas [2–4], and more limitations are expected in the future [5]. However, sludge incineration is regarded as an effective sludge disposal method [2,6,7], which can reduce the sludge volume, destroy toxic organic compounds, and recover the energy content from sludge [8], although the application of PDS sludge mono-incineration is

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limited due to its high moisture content and low calorific value. Many researchers have indicated that the co-combustion of coal and sludge in coal power plants may be a reliable solution that can recycle energy with appropriate controls [2,9,10].

The characteristics of sludge obviously affect NO_X emissions and the conversion rate of fuel NO_X. The N content of sludge is several times higher than that of coal, thereby generating higher NO_X emissions during the combustion process [2]. Furthermore, fuel ignition delays and temperature decreases are caused by the higher moisture content of the sludge, which might have dual effects on NO_X emissions. Moreover, the distribution of secondary air (SA) will affect the combustion temperature and NO_X emissions [11]. The NO_X emissions vary after blending with sludge, which requires great attention to the control of NO_X emissions according to standard emissions limitations. Therefore, it is important to investigate the impact of blending with sludge on NO_X emissions.

Compared with coal, sludge is high in moisture and volatile matter, but it has a low fixed carbon and calorific value [12], which affects the combustion efficiency and combustion profiles [13]. Thus, it is necessary to determine the co-combustion characteristic of coal blended with sludge. Recently, many studies have focused on the kinetic analysis of coal co-combustion with paper mill sludge [3] as well as coal with different types of sewage sludge [1,6,14]. A study of the co-combustion of coal and wastewater sludge showed that the pollutant emissions were higher than that with coal combustion alone, and the amount of sludge in the mixture was identified as a limiting parameter [5]. Furthermore, Singhet al. [15], Ghenai and Janajreh [16], and Gungor [17] indicated that computational fluid dynamics (CFD) analysis can help to optimize the combustion process and provide specific design solutions for power plants. In addition, Lin and Ma [8] showed that semi-dried sludge is more appropriate for co-combustion because of its greater lower heating value and lower moisture content according to CFD simulations. However, few studies have considered the co-combustion characteristics and NO_X emissions of coal blended with PDS in various proportions and at different moisture levels in pulverized coal power plants. Therefore, investigation of the optimal conditions for coal co-combustion with PDS may help to exploit the energy potential of PDS in pulverized coal power plants.

The aim of this study was to determine the co-combustion characteristic and NO_X emissions of coal blended with PDS based on CFD analysis using various PDS levels, PDS moisture contents, and SA ratios. Furthermore, the overall temperature level and NO_X emissions were analyzed to determine the optimal PDS content, moisture content, and SA distribution based on CFD simulations of a pulverized coal power plant.

2. Materials and methods

2.1. Materials and measurements

The coal type considered in this study was bituminous coal from Shanxi Province, China. The PDS considered in this study was obtained from a PDS treatment plant in Guangzhou, China. The proximate analysis and elemental analysis of coal and PDS are shown in Table 1.

In this study, the softening temperature of the ash was measured using an ash fusibility instrument which had a temperature accuracy of 3 °C. Moreover, the temperature and NO_X emissions of the furnace outlet were obtained from an actual operating power plant, where the measurement accuracies for temperature and NO_X emissions were 5 °C and 5 ppmv, respectively. All of the experiments were performed five times to ensure the accuracy of the experimental results. In addition, the simulation results were in agreement, where the variations in temperature and NO_X emission were less than 10^{-4} and 10^{-6}, respectively.

2.2. Computational conditions

The focus of this study was a 420 t/h pulverized coal boiler in Guangzhou, China, where the excess air ratio was maintained at 1.2 in different conditions. The air required for fuel combustion in the boiler was supplied by primary air and SA. The proportion of primary air relative to SA was 3:7, where the primary air was injected into the boiler with the fuel. The primary air and SA were heated by flue gas from the ambient temperature to 373 K and 556 K, respectively.

This study comprised three main parts. In the first part, we performed a comparative analysis of coal blended with different amounts of PDS. The Chinese national policy encourages factories to deal with sludge via efficient combustion and energy utilization. Moreover, coal-fired power plants receive a corresponding subsidy from the government after disposing of the sludge. Furthermore, the combustion of coal blended with sludge can reduce the amount of coal used. Thus, from an economic perspective, the blending of more sludge with coal during the combustion process is more beneficial for coal-fired power plants. However, if the sludge has a high moisture content and a low calorific value, it is difficult to achieve the combustion temperature requirement of the boiler when an excessive amount of sludge is blended during the combustion process. Therefore, this part of the study focused on determining the most economical and reasonable amount of PDS to use in the co-combustion process, where the total lower calorific value of fuel was kept constant in different conditions. The moisture content of the PDS was kept at 20%, but the proportion of PDS (thermal basis) was tested at 0%, 3%, 7%, 10%, and 13%.

In the second part, we performed a comparative analysis of coal blended with PDS at different moisture content levels. The moisture content of the sludge provided by the wastewater treatment plant was up to 80%, which was not suitable for direct combustion. To reduce the moisture content, semi-drying and complete drying processes have been developed for the pretreatment of sludge [2,18,19]. In this study, the moisture content of the PDS was about 40% after the semi-drying process. However, the furnace temperature will be lower as the moisture content of the PDS increases, which affects the normal operation of the power plant

Table 1
The elemental analysis and proximate analysis of coal and PDS.

Coal				PDS			
Elemental analysis[a] (wt.%)		Proximate analysis[b](wt.%)		Elemental analysis[a] (wt.%)		Proximate analysis[b] (wt.%)	
C	84.79	Volatile	13.32	C	39.28	Volatile	31.24
H	4.88	Ash	21.96	H	9.87	Ash	25.18
O[c]	8.08	Fixed carbon	56.72	O[c]	41.14	Fixed carbon	5.27
N	1.34	Moisture	8.00	N	5.23	Moisture	38.31
S	0.91	Low calorific value (MJ/kg)	23.37	S	4.48	Low calorific value (MJ/kg)	7.78

[a] On dry ash free basis.
[b] On wet basis.
[c] Calculated by difference, O (%) = 100–C–H–N–S.

Table 2
The specific SA distributions.

Case	Up SA		Middle up SA		Middle down SA		Down SA	
	Speed (m/s)	Proportion (%)	Speed (m/s)	Proportion (%)	Speed (m/s)	Proportion (%)	Speed (m/s)	Proportion (%)
1#	44.44	25	44.44	25	44.44	25	44.44	25
2#	17.78	10	35.55	20	53.33	30	71.10	40
3#	71.10	40	53.33	30	35.55	20	17.78	10
4#	53.33	30	17.78	10	35.55	20	71.10	40
5#	71.10	40	35.55	20	17.78	10	53.33	30
6#	53.33	30	35.55	20	35.55	20	53.33	30

because the furnace temperature cannot reach the combustion requirement. Therefore, we focused on the effect of the PDS moisture content on the boiler combustion characteristics and pollutant emissions during the co-combustion process. The total lower calorific value of fuel was kept constant in different conditions and the PDS content was 10%. The moisture content of the PDS (thermal basis) was tested at 10%, 20%, 30%, and 40%.

The third part of this study aimed to optimize the SA and the specific SA distributions are shown in Table 2. As shown in Table 2, the SA distribution was uniform in case 1#. In case 2#, the SA ratio increased gradually from top to bottom and this distribution was shaped like a “triangle.” In case 3#, the SA ratio decreased gently from top to bottom and this distribution was shaped like an “anti-triangle.” In case 4#, the SA ratio was lowest in the central region but highest in the bottom region. Thus, this distribution was shaped like a “cooling tower.” By contrast, in case 5#, the SA ratio was lowest in the central region but highest in the upper region. Thus, this distribution was shaped like an “inverted cooling tower.” Finally, in case 6#, the SA ratio was 3:2:2:3 from top to bottom, which was shaped like a “waist drum.”

2.3. Numerical simulation methods

CFD is an effective computational technique for studying, predicting, and optimizing the combustion conditions in power plants [8,15]. The commercial CFD software Fluent 14.0 was utilized in this study. The mesh system comprised 865,003 structured cells, which were refined at the important locations, such as burners, primary air nozzles, and SA nozzles. To assess the validity and accuracy of models, several aspects of the models and calculation methods were considered, as follows.

(1) Standard modeling equations were employed such as the conservation of mass, energy, momentum, and species concentration [20].
(2) The species transport model was combined with a discrete phase model [21] to simulate fuel combustion in the pulverized coal boiler.
(3) The standard κ–ε turbulence model was used to simulate the turbulent gas flow in the pulverized coal boiler [22].
(4) The P-1 radiation model was used to calculate the radiation heat transfer [23], which affected the combustion and particulate behavior.
(5) The surface reaction of fuel combustion was modeled by the kinetics/diffusion-limited rate model [24,25].
(6) The NO_X model mainly considered thermal NO_X and fuel NO_X, where the equilibrium model was used to simulate the thermal NO_X, whereas the solid fuel type NO_X model was employed to calculate the fuel NO_X [26,27].

3. Results and discussion

3.1. Coal mono-combustion and model validation

In order to validate the reliability of the model employed in this study, coal mono-combustion was simulated first in the pulverized coal boiler. Moreover, the boundary conditions of the model used the actual operating conditions employed by the boiler. The actual conditions were obtained from the 420 t/h pulverized coal boiler in Guangzhou, China. The modeling results were obtained from the simulations. The simulation results and the actual results based on the furnace outlet parameters are shown in Table 3.

As shown in Table 3, compared with the actual results in terms of the furnace outlet temperature and NO_X emissions, the errors in the simulation results were only 1.85% and 0.64%, respectively, i.e., far less than the engineering error range (20%). Thus, this model satisfied the simulation requirements for temperature and NO_X emissions. Moreover, the oxygen content of the furnace outlet fluctuated from 1.6% to 3.8% during actual operation. The oxygen content was 2.01% according to the simulation results, which provided the perfect combustion conditions. Thus, this model satisfied the demands for simulating the oxygen content.

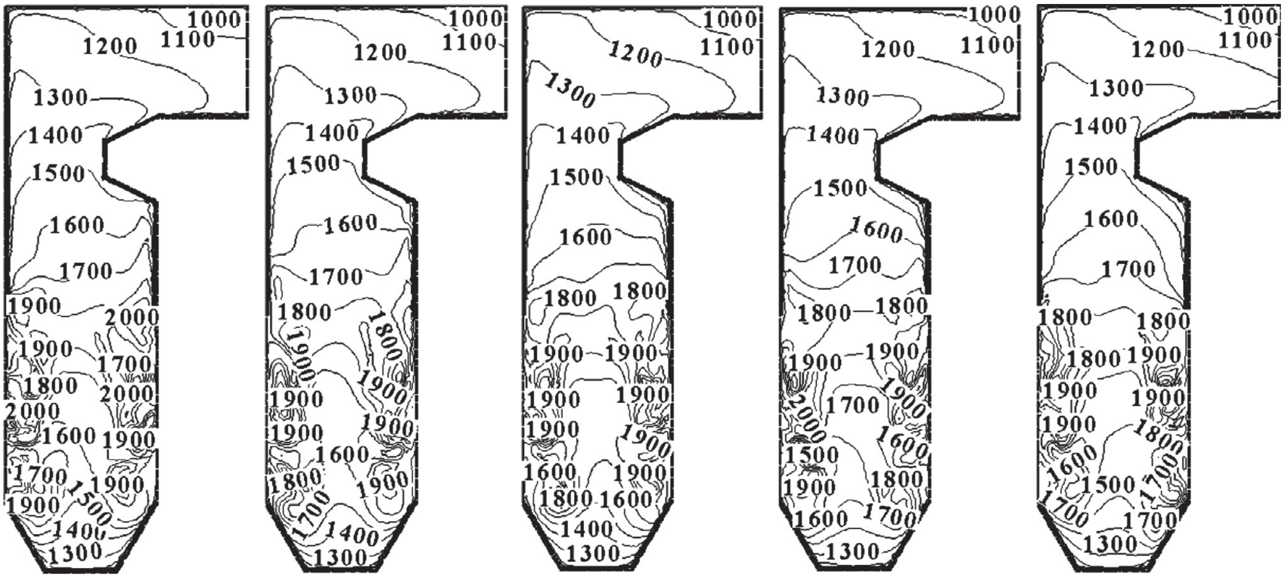
3.2. Different PDS content

The profiles of the temperature and NO_X emissions (dry basis, 6% O_2) for coal blended with different amounts of PDS in the boiler furnace are shown in Figs. 1 and 2, respectively. Furthermore, the detailed parameters for the simulation results and the softening temperature of the ash are shown in Table 4.

As shown in Fig. 1, the temperature profiles were similar for coal blended with different amounts of PDS in the boiler furnace. The high temperature areas were concentrated mainly in the burner region, i.e., between 1800 K and 2000 K. Due to the supply of primary air and SA, the temperature of some areas in the burner region was reduced to 1500–1700 K, but this did not affect the overall high temperature region. Compared with coal mono-combustion (0% PDS), the temperature in the high temperature region of coal blended with different amounts of PDS was slightly lower (50–100 K), whereas the temperature was similar in the area from the burner outlet to the flue outlet.

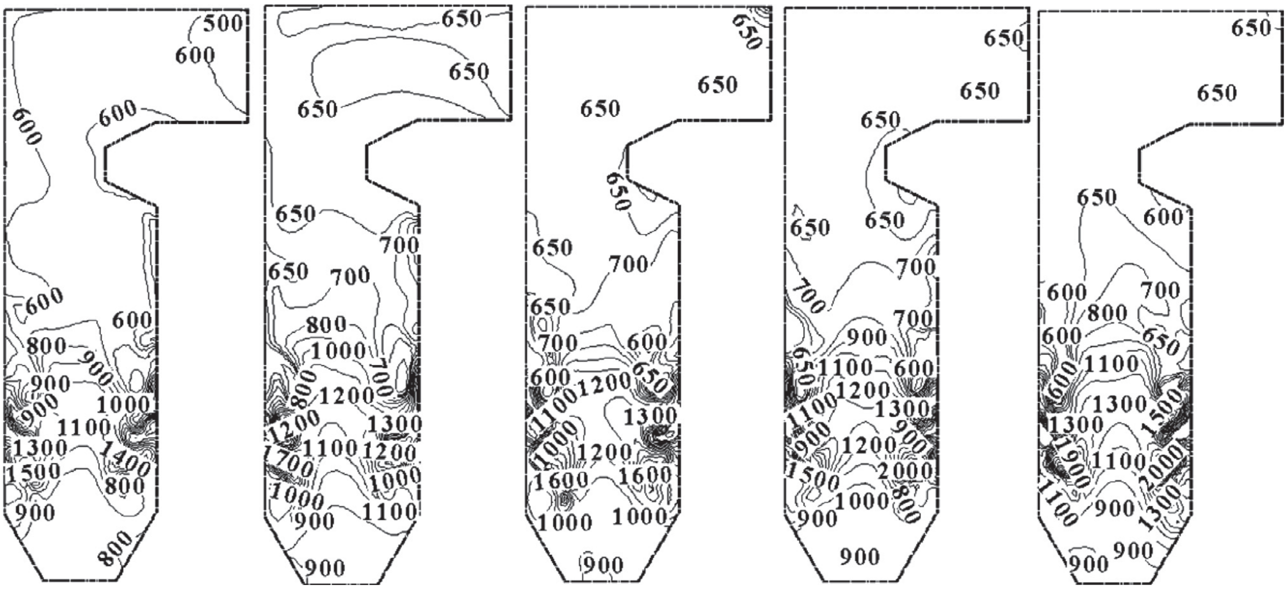
Table 3
The comparison of the simulation result and actual results based on the furnace outlet parameters.

Parameter	Simulative result	Actual result	Error
Temperature	1399.9 K	1374.0 K	1.85%
Oxygen content	2.01%	1.6–3.8%	Within the actual range
NO_X emission	553.0 ppmv	550.0 ppmv	0.64%



(a) 0% (b) 3% (c) 7% (d) 10% (e) 13%

Fig. 1. The profiles of the temperature for coal blended with different amounts of PDS in the boiler furnace (K).



(a) 0% (b) 3% (c) 7% (d) 10% (e) 13%

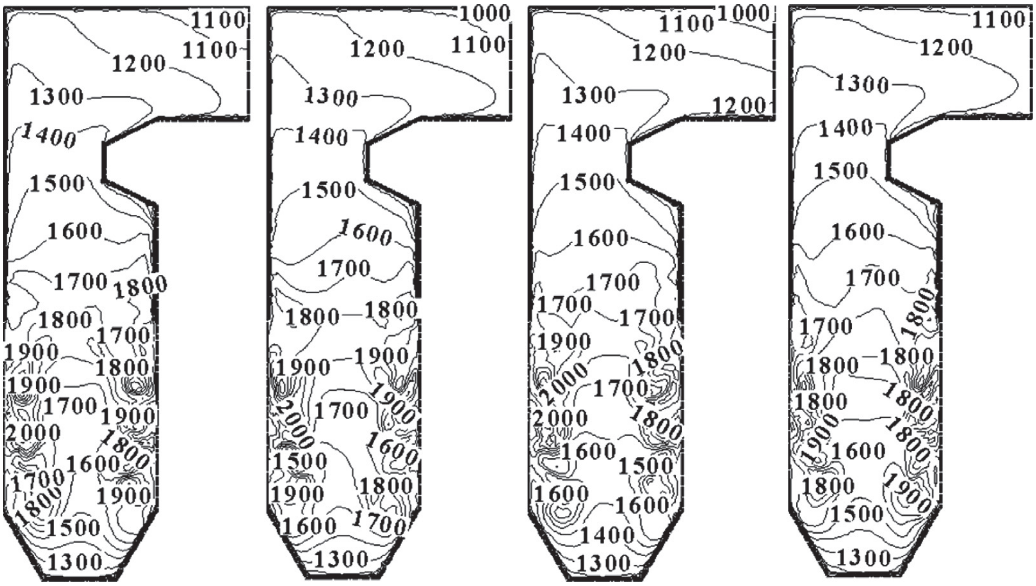
Fig. 2. The profiles of NO_X emissions (dry basis, 6% O_2) for coal blended with different amounts of PDS in the boiler furnace (ppmv).

Table 4
The detailed parameters for the simulation results and the softening temperature of the ash under coal blended with different PDS content.

Different PDS content (%)	Temperature of furnace outlet (K)	H_2O (%)	NO_X (dry basis, 6% O_2, ppmv)	Softening temperature (K)
0	1399.9	5.5	553.5	1595
3	1398.6	6.3	629.9	1497
7	1397.0	7.3	673.5	1419
10	1394.9	7.8	681.8	1400
13	1391.7	8.4	682.8	1391

In addition, as shown in Table 4, the flue gas temperature of the furnace outlet decreased slightly as the PDS content increased. This was mainly because the amount of fuel increased in a corresponding manner after blending with PDS based on a constant total lower calorific value. The furnace temperature was similar in the different conditions. However, Table 4 indicates that the H_2O concentration of the flue gas clearly increased with the PDS content. Thus, due to the evaporation of water in the furnace, the overall temperature in the furnace decreased slightly as the PDS content increased.

As shown in Fig. 2, the NO_X emissions were similar for coal blended with different amounts of PDS in the boiler furnace, where the high concentration areas were focused mainly in the burner region. Due to the high temperature region, a large amount of thermal NO_X was produced, i.e., between 1000 ppmv and 1600 ppmv, and the levels even reached 2000 ppmv in local high temperature areas. Moreover, as shown in Table 4, the NO_X emissions increased gradually with the PDS content, as found in previous studies



(a) 10% (b) 20% (c) 30% (d) 40%

Fig. 3. The profiles of the temperature for coal blended with PDS at different moisture contents in the boiler furnace (K).

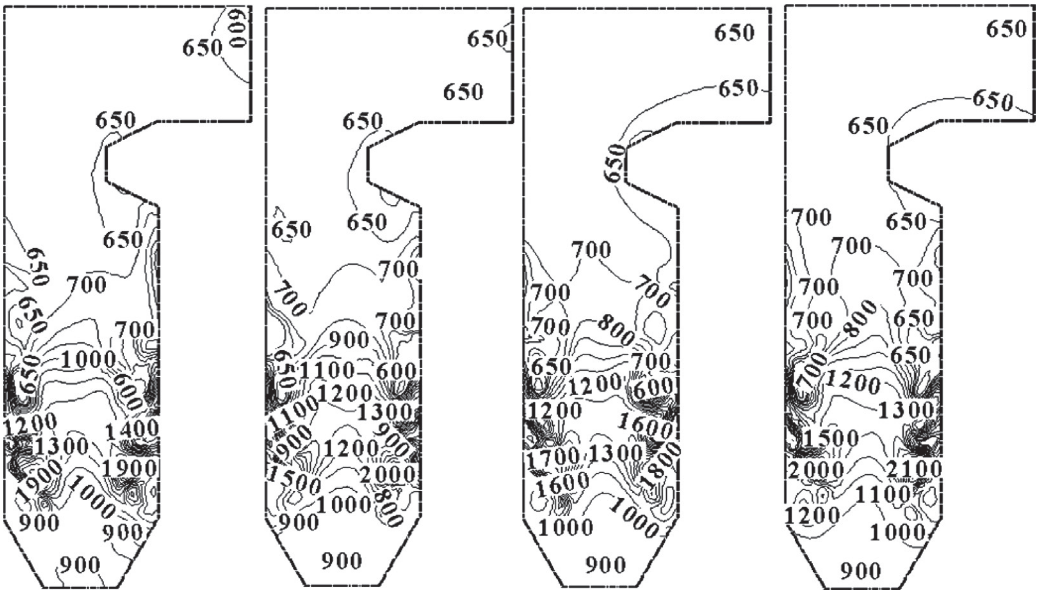
[5,6,14]. This was because the N content of PDS (5.23%) was much higher than that of coal (1.34%) and the fuel NO_X emissions increased as the amount of PDS in the fuel mixture increased. Previously, Nadziakiewicz et al. [5] performed experiments in an experimental boiler, where the NO_X emissions from coal blended with 10% sludge increased by 22.73% compared with coal mono-combustion (from 110 to 135 mg/N m^3). In our study, as shown in Table 4, the NO_X emissions from coal blended with 10% PDS were increased by 23.18% compared with coal mono-combustion, which was similar to the previous study. The main variations were due mostly to differences in the fuel components and the boiler characteristics.

As shown in Table 4, the softening temperature of the fuel decreased markedly as the PDS content increased. When the PDS content was 13%, the softening temperature was only 1391 K, which was almost equal to the flue gas temperature of the furnace outlet. This could cause scorification and corrosion of the platen superheater, or tubes might even burst. Therefore, these conditions would severely affect the safety and economy of a power plant.

Our analysis indicates that based on a constant total lower calorific value, blending with 10% PDS is feasible after considering the combustion characteristics, NO_X emissions, and softening temperature of ash.

3.3. Different PDS moisture contents

The profiles of the temperature and NO_X emissions (dry basis, 6% O_2) for coal blended with PDS at different moisture contents in the boiler furnace are shown in Figs. 3 and 4, respectively. The detailed parameters of the simulation results are shown in Table 5.



(a) 10% (b) 20% (c) 30% (d) 40%

Fig. 4. The profiles of NO_X emissions (dry basis, 6% O_2) for coal blended with PDS at different moisture contents in the boiler furnace (ppmv).

Table 5
The detailed parameters of the simulation results under coal blended with PDS at different moisture contents.

Moisture content (%)	Temperature of furnace outlet (K)	H_2O (%)	NO_X (dry basis, 6% O_2, ppmv)
10	1395.8	6.8	665.9
20	1394.9	7.8	681.8
30	1389.8	8.3	689.2
40	1387.7	9.0	703.2

As shown in Fig. 3, the temperature profiles were similar for coal blended with PDS at different moisture contents in the boiler furnace. The high temperature areas were concentrated mainly in the burner region, i.e., between 1600 K and 2000 K. In addition, the flue gas temperature in the furnace outlet decreased gradually as the moisture content of the PDS increased from 10% to 40%. For example, the furnace outlet temperature with 40% moisture was only 8.11 K lower than that with 10% moisture. This was mainly because after blending with the high moisture content PDS, the amount of fuel increased in a corresponding manner based on the constant total lower calorific value. Hence, the furnace temperature could satisfy the combustion requirement, thereby indicating that the overall temperature level was similar. However, as shown in Table 5, more H_2O was generated in the co-combustion process because the moisture content of the PDS was higher. Thus, due to the evaporation of water in the furnace, the overall temperature level of the furnace decreased slightly as the moisture content of the PDS increased.

As shown in Fig. 4, the NO_X emissions were similar for coal blended with PDS at different moisture contents in the boiler furnace, where they were concentrated mainly in the burner region. Moreover, Fig. 4 and Table 5 show that the NO_X concentration increased gradually as the moisture content of the PDS increased. There are two possible explanations for these results. First, fuel ignition was delayed because of the high moisture content of the PDS. However, there was sufficient time to supply O_2 to the fuel ignition region and the O_2 concentration then increased in the fuel ignition region. Furthermore, due to the ignition delay, the residence time of nitrogen increased in the high temperature region. Thus, the formation of NO_X was promoted, thereby resulting in an increase in the fuel NO_X. Second, the overall temperature level of the furnace decreased gradually due to the increased moisture content of the PDS. Thus, the thermal NO_X decreased slightly. However, the increase in the fuel NO_X was greater than the decrease in the thermal NO_X [28]; therefore, the total NO_X emissions increased as the moisture content of the PDS increased.

According to this analysis, the furnace temperature was lower and the NO_X emissions were higher as the moisture content increased. However, when 1 ton of wet PDS with a moisture content of 80% was dried to 10%, 20%, 30%, and 40%, the heat consumption levels were calculated as 2.03 GJ, 1.96 GJ, 1.88 GJ, and 1.77 GJ, respectively. Thus, the cost of the drying treatment decreased as the moisture content increased, thereby improving the economy of the power plant. In this study, after the semi-drying treatment, the moisture content of the PDS was 40%. In this case, the furnace outlet temperature for coal blended with 10% PDS was 1387.68 K, which satisfied the temperature demand of the boiler furnace outlet (>1273–1373 K). In addition, the NO_X emissions level from the furnace outlet was 703.2 ppmv and the SCR denitration efficiency of the actual operation in the power plant was >90%. Thus, the NO_X emissions level in the chimney was <70.3 ppmv, which satisfied the environmental requirements (<80.0 ppmv).

In summary, blending coal with 10% PDS at a 40% moisture content is feasible and reasonable given the economic evaluation, combustion characteristics, and NO_X emissions.

3.4. Different SA ratios

The SA distribution also affects the combustion temperature, and CO and NO_X emissions [11]. Thus, it is possible to optimize the combustion characteristics and reduce the pollutant emissions by changing the SA ratio [29]. In this part of the study, the PDS content was 10% and the moisture content of the PDS was 40%, whereas the SA distribution was varied, as shown in Table 2. Furthermore, the profiles for the temperature, and CO and NO_X emission (dry basis, 6% O_2) with different SA ratios in the boiler furnace are shown in Figs. 5 and 6, respectively. The detailed parameters for the simulation results obtained with different SA ratios are shown in Table 6.

As shown in Fig. 5, in case 3#, the temperature in the bottom region of the burner was quite low due to a lack of oxygen, which caused inadequate combustion and the production of large volumes of CO. However, the adequate oxygen level in the upper region of the burner ensured adequate combustion, thereby resulting in a high temperature. In general, the high temperature region moved up. Moreover, the combustion conditions were not ideal.

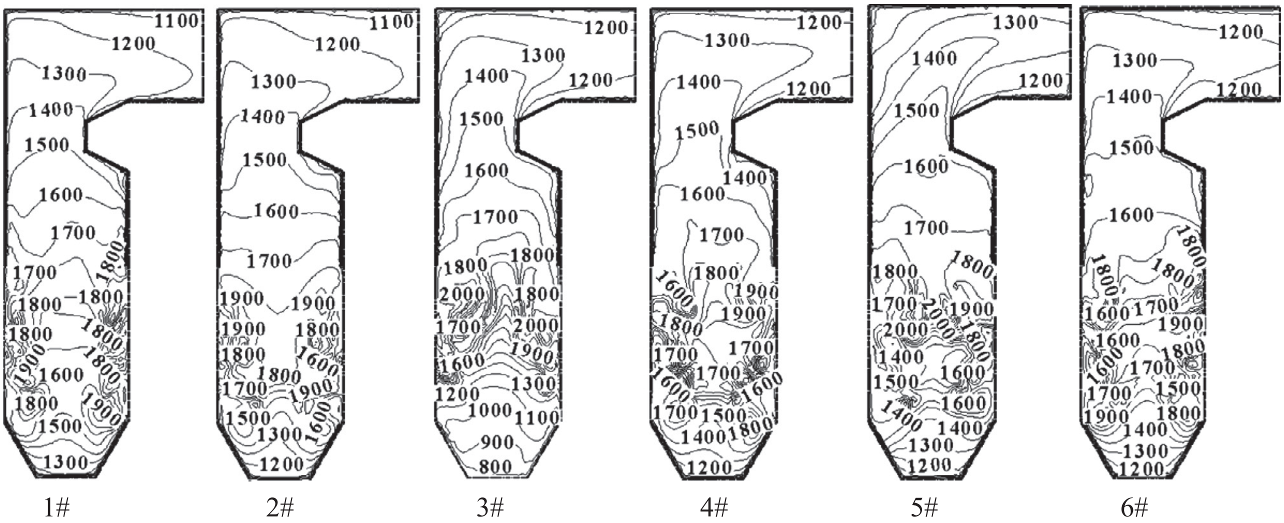


Fig. 5. The profiles for the temperature with different SA ratios in the boiler furnace (K).

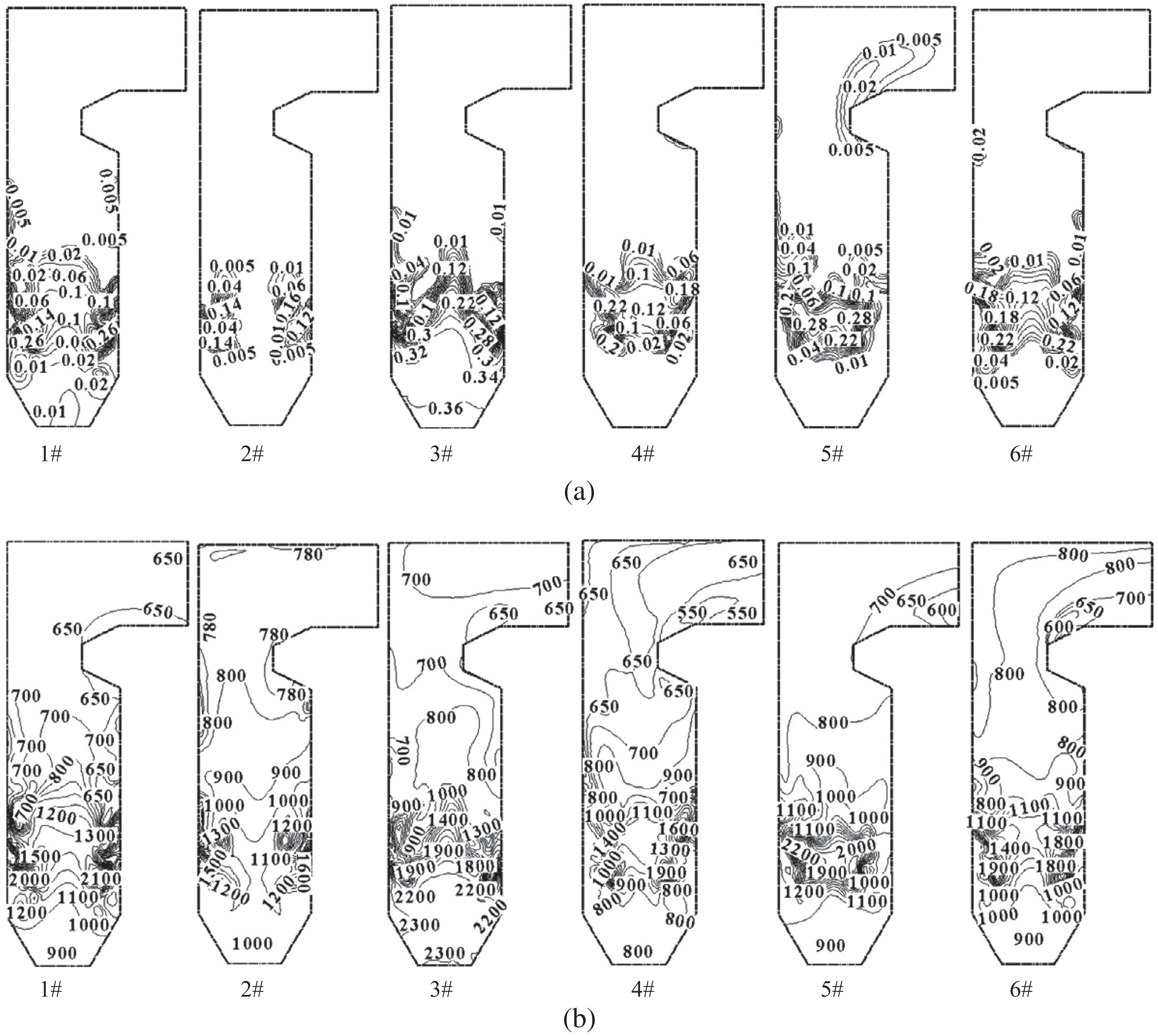


Fig. 6. The profiles for CO emission (a, %) and NO_X emission (b, dry basis, 6% O_2, ppmv) with different SA ratios in the boiler furnace.

Table 6
The detailed parameters for the simulation results obtained with different SA ratios.

Case	Temperature of furnace outlet (K)	H_2O (%)	NO_X (dry basis, 6% O_2, ppmv)
1#	1387.7	9.0	703.2
2#	1381.8	9.1	745.8
3#	1398.7	8.4	646.0
4#	1405.5	8.2	544.8
5#	1415.4	8.7	625.6
6#	1402.0	7.8	646.4

Thus, case 3# was not a good SA distribution scheme. By contrast, the temperature conditions were similar to case 1# in the other cases. As shown in Table 6, the furnace temperature was high in case 5#, which was not a reasonable SA distribution scheme. However, the combustion requirements were satisfied in the other cases.

As shown in Fig. 6 and Table 6, the NO_X emissions were lowest in case 4#, where a large volume of oxygen was supplied to the bottom region of the burner. Due to the low temperature, the thermal NO_X consumption was reduced in this region. In the central region of the burner, the oxygen supply was then reduced in order to produce more CO, thereby inhibiting the formation of NO_X. In addition, a large volume of oxygen was supplied to the upper region of the burner to ensure the absolute combustion and consumption of the CO produced in the central region. Thus, the temperature satisfied the combustion requirements.

According to this analysis, case 4# was the best SA distribution scheme and the SA ratio was 3:1:2:4 from top to bottom.

4. Conclusions

Based on this analysis, the overall temperature level in the furnace decreased slightly as the PDS content increased, while the NO_X emissions increased gradually. Moreover, after increasing the moisture content, the overall temperature level was lower in the furnace but the NO_X emissions were higher. Furthermore, based on a constant total lower calorific value, blending coal with 10% PDS at a 40% moisture content was shown to be feasible and reasonable given the combustion characteristics and NO_X emissions. The SA distribution clearly affected the combustion characteristics and pollutant emissions, and case 4# was found to be the best SA distribution scheme, where the SA ratio was 3:1:2:4 from top to bottom.

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